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iRobot was tasked to develop a new payload module and to construct two new vehicles in support of ongoing research at Stevens Institute of Technology. These vehicles were to be equipped with DVL (Doppler Velocity Logs) sensors, enabling more precise navigation while underwater and minimizing the need to surface for frequent GPS fixes. The Ranger payload module was designed to incorporate this and other sensors, while the Transphibian DVL was externally mounted at the rear of the system. These AUVs were delivered in early 2010. This document describes the activities related to this project.

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Robots that make a difference

Final Report

Integration of UUV-Based Mobile Sensor Nodes with a Model-Assisted Wide Area Surveillance System for Persistent Maritime Scene Awareness in support of the Maritime Security Laboratory (MSL)

N00014-08-C-0198

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22 April 2008 – 30 June 2010

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1 EXECUTIVE SUMMARY

iRobot was tasked to develop a new payload module and to construct two new vehicles in support of ongoing research at Stevens Institute of Technology. These vehicles were to be equipped with DVL (Doppler Velocity Logs) sensors, enabling more precise navigation while underwater and minimizing the need to surface for frequent GPS fixes. The Ranger payload module was designed to incorporate this and other sensors, while the Transphibian DVL was externally mounted at the rear of the system. These AUVs were delivered in early 2010. This document describes the activities related to this project. Figure 1 shows the Ranger operating in the Hudson River during a joint Stevens Institute-iRobot deployment in May 2010.

Figure 1: Ranger Operating in the Hudson River during May 2010 Tests

2 RESEARCH OBJECTIVES

The objectives of this effort were to develop vehicles and systems to enable Stevens Institute to further their research into developing harbor observation systems with mobile sensor nodes. The vehicles provided allow varied behaviors to be investigated. For example, Ranger allows long-duration free-swimming operation, while Transphibian enables research into methods of more direct interaction with the boundaries of the waterspace, including active inspection of infrastructure or landing on the bottom to wait out adverse tidal cycles.

3 RESEARCH METHODS

Stevens Institute has been using Ranger RN-2 UUVs to support its research since their initial tests in July, 2007 [1] [2]. These vehicles are equipped with vectored thruster, GPS, WHOI micromodem, conductivity and temperature sensors, 802.11 radios, and payload processors. These vehicles have been useful to conduct initial experiments and to understand the relevant operational requirements. The main limitation of the Ranger RN-2 vehicles in the estuarial environment is the lack of underwater navigational sensor (The WHOI micromodem can operate as an LBL, however with very limited performance in that environment). This limitation leads to very large navigation errors, since currents are strong, multi-layered, and change rapidly with both location and time. To keep positional uncertainty within reasonable bounds, the UUV is required to surface frequently to obtain GPS fix. This is undesirable, since it disrupts the mission profile and exposes the UUV to the risk of collision with boat traffic.

The Explorer DVL (Doppler Velocity Log) provided an attractive solution to this problem. Small enough to be integrated onto a man-deployable AUV such as the Ranger, it can provide bottom-referenced vehicle velocity measurements. This enables the UUV to remain underwater much longer without building up as much positional uncertainty. This DVL was packaged and integrated into two AUVs: Xfin Ranger and Transphibian. For Ranger, a new payload module was developed that increased battery capacity and included Conductivity (C), Temperature (T), and Dissolved Oxygen (DO) sensors. The DVL was installed amidships for trim and balance. For Transphibian, the DVL was packaged in a new housing at the aft end of the vehicle, leaving the forward payload port available for an imaging sensor in the future. Environmental sensors (CT and DO) were located in the side buoyancy tubes.

4 RESEARCH RESULTS

4.1 RANGER PAYLOAD DEVELOPMENT

The DVL was specified with current profiling, bottom lock, and short range options. Custom cables were specified to enable compact integration with the vehicle. Drivers were written to interface the unit to the MOOS (Mission Oriented Operating Suite [3]) database used by the vehicle. Substantial effort was spent in validating the operation of the sensor, using both the custom drivers as well as the Windows utilities provided with the hardware, and testing both in the freshwater test tank and a local lake with substantial suspended matter. Another cycle of testing was performed following the return of the unit to the factory for checkout. After similar results were obtained, the transducer head was exchanged with a known good unit from the manufacturer and the sensor began reporting good data.

Eureka environmental sensors were selected to provide conductivity, temperature, and dissolved oxygen measurements. They are placed in the nose of the vehicle inside a protective flow-through cage. The sensors are compact size, and digitize the measurements directly at the sensor. This eliminates analog cabling within the hull that could be susceptible to interference from other electronics.

The vehicle mast contains the GPS antenna, GPS receiver, and the antenna for the cell phone modem. The GPS antenna is attached directly to the GPS receiver without any intermediate wiring. The GPS signal is digitized in the antenna and passed down into the vehicle which reduces the opportunity for signal interference. The cell phone modem allows long distance communications while the vehicle is surfaced.

The transducer for the WHOI micromodem was placed on the bottom of the hull. The port for the acoustic transducer is the same as for the mast, allowing the option of removing the mast and placing the acoustic transducer on the top of vehicle to improve communications if desired for particular missions.

4.2 FABRICATION OF RANGER VEHICLE AND PAYLOAD

The nose cap of the vehicle (Figure 2) was designed to allow free flow of water to the environmental sensors while protecting them from physical damage. It was fabricated using a rapid prototyping process to allow rapid geometry changes if different nose sensor configurations were required, and inexpensive replacement in the event of damage.

Figure 2: Ranger with ADCP and Environmental Sensor Payload

The mast was fabricated by attaching the various antennas to a mechanical spine. Prior to attachment, the GPS receiver was encapsulated in a rigid potting material to protect it from pressure effects. Once the antennas were attached to the spine, the assembly was encapsulated in a flexible potting compound to give it a faired shape.

The On/Off switch uses a rotating barrel to actuate a mechanical switch inside the hull. This eliminates the need for activation magnets, and reduces the chances of an accidental power switch change.

The payload subsystems inside the vehicle were assembled as independent modules that slide onto internal stress rods (Figure 3). Once the modules are assembled and interconnected, the hull is slid on. The rear payload module then attaches to the stress rods and is tightened to complete the payload assembly.

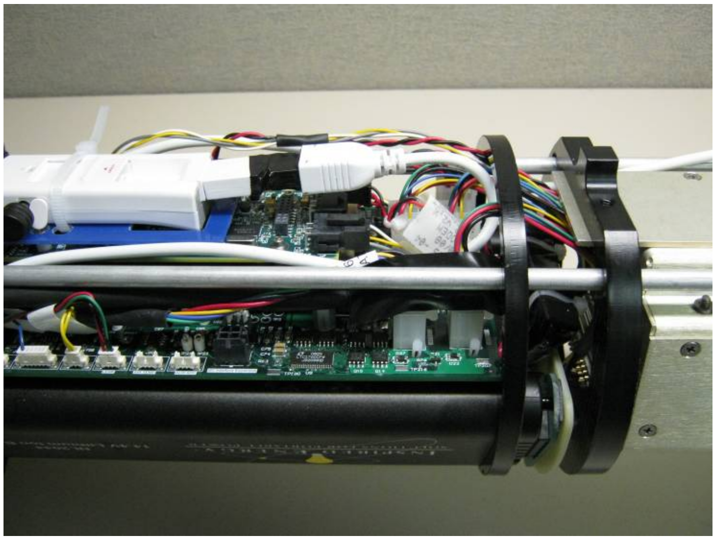

Figure 3: Internal View of Ranger Payload showing Stress-rod Construction

The tail section assembles in a similar fashion with the components mounting to a skeleton structure. The hull is them slid over top, and internal stress rods are tightened to pull the hull sections together and complete the tail assembly.

The tail assembly is attached to the payload assembly by connecting the various electrical connectors between the sections, sliding the sections together, and securing them with radial screws.

4.3 FIELD TESTING

System field testing for the Ranger began in an indoor pool to characterize the performance of the vehicle and to begin to tune the control parameters (Figure 4).

Figure 4: Ranger Undergoing Pool Testing in North Carolina

After initial pool testing, further testing was conducted in Lake Elton to tune yaw parameters and to validate high-level system operation including navigation and mission handling. Figure 5 shows the Ranger dockside during testing in Lake Elton.

Figure 5: Ranger during Field Testing in North Carolina

After field tests, the Ranger was disassembled for shipment to Stevens Institute (Figure 6). Disassembly and reassembly is facilitated by the modular construction of the vehicle, allowing the tail and nose sections to be easily removed for shipping in conveniently sized cases.

Figure 6: Ranger Packed for Shipment

4.4 DEMONSTRATION

3 days of joint operations (11-13 May, 2010) with iRobot and Stevens Institute personnel were conducted to train the Stevens personnel in the operation of the vehicle and to collect initial in-situ data. Classroom training was provided on day 1, with field operations in the Hudson River on day 2, and post-mission analysis on day 3. Field operations were conducted from the R/V *Savitsky*, operated by Stevens Institute. Figure 7 depicts the Ranger aboard the vessel during tests.

Figure 7: Ranger on Deck during Testing in the Hudson River, May 2010

A total of 10 runs were conducted by the team. Several observations were noted related to the performance of the system, including:

- Remaining at the surface in spite of commanded depth run (this was discovered to be due to conflicting script parameters of porpoise time and timeout)

- Incorrectly computing navigation when GPS was unavailable (coding error discovered and corrected during post mission analysis of log file)
- Uncommanded dive during surface run and poor control performance in turbulent operating waters. iRobot has examined these issues and traced them down to hardware, including a temperature instability in the actuator feedback system and an unbalanced ground path in the drive motor. In addition to resolving these problems, iRobot has integrated a higher-performance IMU and installed fins with greater control authority.

4.5 FABRICATION AND BUILD OF TRANSPHIBIAN

A Transphibian vehicle was built to match the version used on the Feature-Based Navigation (FBN) program funded under ONR Code 321. Standard features of this vehicle include, GPS, 700 WHrs of batteries, camera, 3-axis compass, and 802.11 RF buoy.

Customizations included the integration of environmental sensors (conductivity, temperature, and dissolved oxygen) into the side buoyancy tubes, WHOI micromodem, Geode PC104-based payload processing stack, and the integration of the ADCP module in an aft-mounted module.

Tank testing of Transphibian was done to ensure proper operational trim using the new ADCP module. Testing was also conducted at Lake Elton, NC to exercise low-level (fin motion, sensor functionality) and high level (navigation, mission execution) vehicle functions prior to shipment to Stevens Institute. Figure 8 and Figure 9 show Transphibian undergoing tests at Lake Elton.

Figure 8: Transphibian with ADCP and Environmental Sensors Installed during Initial Field Tests

Figure 9: Transphibian during Field Testing in North Carolina

The Transphibian vehicle was packed and shipped to Stevens Institute in February 2010 (Figure 10).

Figure 10: Transphibian during Packing for Shipment

4.6 ADDITIONAL PROJECT AND VEHICLE SUPPORT

4.6.1 Hydro Analysis

Stevens Institute was contracted to conduct a hydrodynamics analysis of the Ranger body and fins using their computational fluid dynamics (CFD) package. Results were provided in the form of tables and charts detailing steady forces and moments on the vehicle as a whole, and on the vehicle body and the control fins. Simulations were performed with the vehicle describing steady turns with three different radii (1.5m, 2.5m, and 3.5m), four different speeds (0.5kts, 1.5kts, 2.5kts, and 3.5kts) and four different fin offset positions (4^{o}, 8^{o}, 12^{o}, 14^{o}) for a total

of 48 separate simulations (see Figure 11 for example graphical results). The effective vehicle drag coefficient estimate varied with velocity between 0.22 and 0.31 for the highest radius turn (3.5m.) At the low radius turn (1.5m) the drag coefficient in surge appears to dominated by turning effects, making the results (which vary between 0.2 and 0.35) less applicable.

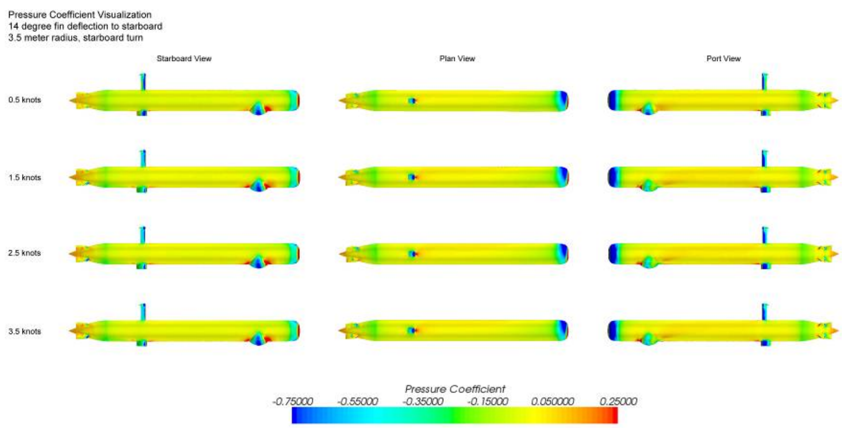

Figure 11: Example of Graphical Results of Hydroanalysis conducted by Stevens Institute (Pressure Coefficient Visualization at 14 degree fin deflection during 3.5m radius turn)

Several vehicle parameters can be indirectly estimated from the results, included the control fin lift coefficient slope, linear and quadratic moment coefficients in yaw. A number of important coefficients that are required to determine dynamic stability margins are not accessible with these results, however, and a future program would be well served with a set of simulations targeted at decoupling various vehicle forcing modes in order to directly produce valuable parameters. In particular, pure surge simulation with varying fin position, and simulations with small body angles of attack (surge with side-slip and surge with slow depth change) would be valuable.

4.6.2 Vehicle Operations Support

In addition to the joint operations in the Hudson in May 2010, iRobot provided remote engineering support to Stevens Institute for their operations of the Ranger RN2 (Vectored Thruster vehicles) in New Jersey and Florida, and operation of the Transphibian vehicle in New Jersey.

5 CONCLUSIONS AND LESSONS LEARNED

- The Transphibian platform has proven to be very flexible, in accepting a rear-mounted DVL and side mounted CT probes while eliminating the front mounted sonar module that was used on its two sister vehicles constructed for the Feature-Based Navigation project. This leaves the front position free to accept a sonar or other sensor in the future as new research needs arise.
- The Ranger module design successfully incorporated all required payload functions, and added additional functionality through the integration of the micromodem, cell modem, and dissolved oxygen sensor.
- The Eureka Manta2 environmental sensor suite was straightforward to integrate mechanically and electrically. Its software interface lends itself well to use in a MOOS system.

6 ACKNOWLEDGEMENTS

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7 RIGHTS IN TECHNICAL DATA AND SOFTWARE

The technical data making up the design of the robots being delivered on this Contract (the "Robots"), the Robot's parts and components, and the computer software embedded on the Robots are being provided to the Government with less than unlimited rights. Such technical data and software are subject to data and software restrictions contained in Appendix A hereto.

8 REFERENCES

[1] Matson, E. "Final Report – The Development of a Free-Swimming UUV for MCM Reacquisition and Neutralization." August 2009. Sponsored by Office of Naval Research, Code 321.

[2] Sammut, P., M. Tsionskiy, A, Sedunov, J. Dzielski, M. DeLorme. "Remote Control and Monitoring of MOOS Vehicles through Cellular Modems." Presented at MOOS Development and Applications Working Group, Cambridge, MA, August 24-25, 2010.

[3] Newman, Paul M. "MOOS – Mission Oriented Operating Suite." Department of Ocean Engineering, Massachusetts Institute of Technology, 2002.

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Technical Data or Computer Software to be Furnished With Restrictions	**Basis for Assertion**	**Asserted Rights Category**	**Name of Person Asserting Restrictions**
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Angstrom Linux	Developed	Commercial	Various

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